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Surface charge influence on the flashover voltage of composite insulator model working at HVDC

***Abstract**. The paper presents the results of research on the influence of the electric charge deposited on composite insulators models on DC flashover voltage. The influence of the charge on the flashover voltage was observed on the level of 0-18%. That influence depended on the insulator position. There was no visible influence (occurrence of any regularity) of core and housing material on a flashover voltage.*

***Streszczenie.** Przedstawiono wyniki badań wpływu ładunku elektrycznego zgromadzonego na modelach izolatorów kompozytowych na napięcie przeskoku przy narażaniu napięciem stałym. Wpływ ładunku na napięcie przeskoku był na poziomie 0-18%. Wpływ ten zależał od położenia izolatora. Nie było żadnego widocznego wpływu (wystąpienia jakichkolwiek regularności) materiału rdzenia i powłoki na napięcie przeskoku (**Wpływ powierzchniowego ładunku elektrycznego na napięcie przeskoku modelu izolatora kompozytowego przy narażeniu napięciu stałym**).*

Keywords: high voltage, DC voltage, composite insulators, surface charge.
Słowa kluczowe: wysokie napięcie, napięcie stałe, izolatory kompozytowe, ładunek powierzchniowy.

Introduction

Development of DC power distribution systems [1,2,3] requires determination and understanding of physical processes leading to a generation and distribution of electrical charge (or related quantities) deposited on insulator surface.

The charge deposited on surface can have impact on both DC [4,5] and impulse [6,7] flashover value U_f. So far carried studies show that surface discharge can result in charging the insulator surface [8-10].In the studies conducted so far with DC voltage (only negative polarity was used) hetero-charge (that is, a charge with opposite polarity as the polarity of the voltage) decreased absolute flashover value, while homo-charge (that is, a charge with same polarity as the polarity of the voltage) increased it. Measured influence was on the level of 10%.

Previous studies have been performed on models equipped with electrodes that their shapes differ from the typical, industrial fittings used on insulators [4-10].

Expanding knowledge of composite insulators and the phenomena occurring during the usage of the HVDC lines can lead to the improvement and efficiency increase of electric power transmission.

Models

The investigations were carried out on a composite insulator models. Each of models consisted of cylindrical dielectric core and silicone elastomer housing, both made of different dielectrics. The insulating cores with diameter equal to 20 mm, were made of epoxy/glass composite (signed EG), basalt/epoxy composite (B) and polyamide PA6 (PA). Two types of silicone coverage were used. One of them was made using Liquid Silicone Rubber technology (signed - LSR) and second – using High Temperature Vulcanization (HTV). Finally there were 6 types of combinations and models signed as follows:

- EG-LSR, EG-HTV – models with EG core and LSR or HTV housing;
- PA-LSR, PA-HTV – models with PA core and LSR or HTV housing;
- B-LSR, B-HTV – models with B core and LSR or HTV housing.

Each of models was equipped with typical, industrially used metal fittings mounted on its ends. Distance between the fittings was for all of models equal to 270 mm and the outer diameter of the insulating part of the model (insulating cylinder) was equal to 25 mm. There were 3 samples of each core housing combination.

Electrical properties of used materials, i.e. the relative permittivity ε_r and electrical volume resistivity ρ_v used material (core and cladding) are shown in Table 1.

For all models half-life time was greater than 200 s [11]

Table 1.Electrical properties resistivity of used materials

Material	Relative permittivity ε_r [-]	Volume resistivity ρ_v [Ωm]
HTV	3,8	$1{,}9\times10^{12}$
LSR	2,6	$2{,}1\times10^{13}$
PA	4,5	$3{,}8\times10^{11}$
EG	5,5	$1{,}2\times10^{12}$
B	5,2	$2{,}2\times10^{11}$

Simulation

Research consisted of two parts: simulation and experimental.

In order to predict influence of surface charge on flashover voltage value U_f. Simulations were carried out in COMSOL Multiphysics v.4.2. A 2D axisymmetric model was made based on real dimensions of tested insulator and high voltage equipment arrangement.

Two insulator position were taken into account (like in experiment): 1) insulator placed vertically with one fitting on grounded metal surface (so called “down” position) and insulator placed vertically, 1.4 m above the ground (so called “up” position). The polarity of applied voltage to upper fitting was positive. In order to simplify calculation it was assumed that the relative permittivity of whole dielectric part is constant and equal to ε_r = 5. In the simulation model the charge was placed in the middle of insulator. The region of surface charge distribution had a shape of a 30 mm long ring (charge was evenly distributed around insulator perimeter). Assumed charge density distribution along generatrix (30 mm) was sinusoidal with maximum value of q_{smax} = +48 μC/m^2 (homo-charge) or -48 μC/m^2 (hetero-charge). This results in maximum electric field around E_{max} = 3 MV/m, which is consider the dielectric strength for air.

Mathematically streamer inception criteria can be written as follow [4,12]:

$$K_{cr} = \int_{0}^{x_{cr}} \alpha_{eff}(E)dx \qquad (1)$$

where: $\alpha_{eff}(E)$ – field dependent effective ionization coefficient, 0 - x_{cr} – distance along so called “critical line” where α_{eff} >0.

The equation to evaluate and the value of K and criteria for streamer propagation were taken from literature [4,13,14].

Line connecting two points with highest electric field on both fittings (between places where housing contacts the fitting) was considered to be the critical line.

Calculated values of flashover voltage with relation (1) are shown in table 2.

Table 2.Flashover voltage value calculated using described criteria

Position	Relative permittivity ε_r [-]	Calculated flashover voltage value U_f [kV]		
		Hetero-charge	No charge	Homo-charge
up	3	151	162	172
up	5	162	174	184
down	5	126	133	141

Average charge influence on calculated flashover voltage is on the level of 6%.

Electric field (modulus value) distributions calculated along critical line for insulator in position “down”, were shown in Fig. 2.

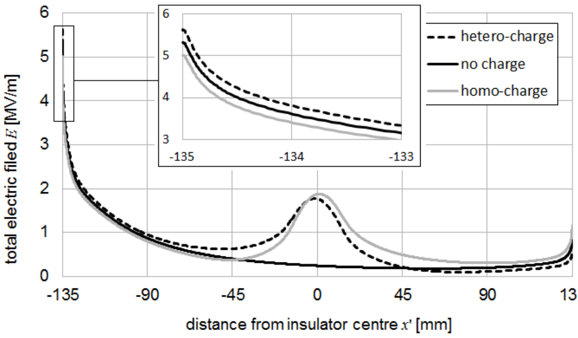

Fig. 1. The distributions of the total electric field $E(x')$ along the critical for the model without charge and with charge of both polarities. The voltage on the HV-fittng was U_{fit} = +133 kV

It can be clearly seen that homo-charge decreases maximum electric field value E_{max} while the hetero-charge increase it. The increase or decrease of electric field value takes place in wide region – 0 – 90 mm near the HV fitting.

Electrification

For the charging of tested samples corona electrification method was used. As a high-voltage power supply a stabilized generator type Glassman EW40P was used. Corona electrode was attached to it by a protective resistor (R = 2.75 MΩ). During the electrification insulator was placed on a grounded plate. Corona electrode was placed 10 mm above insulator centre.

After electrification surface potential and its distribution (along the model generatrix) was measured using an AC compensated voltmeter TREK – Hand-Held Electrostatic Voltmeter Model 520. Probe was placed in a distance of 7 mm above the model surface and operating in the compensating, non-contacting mode. During the measurements fittings of the model were supported by earthed, conducting supports.

Surface charge distribution calculated by Φ-matrix method [14] is showed in Fig. 2. Electrification voltage was U_c = 40 kV and the electrification time was t_c = 10 s.

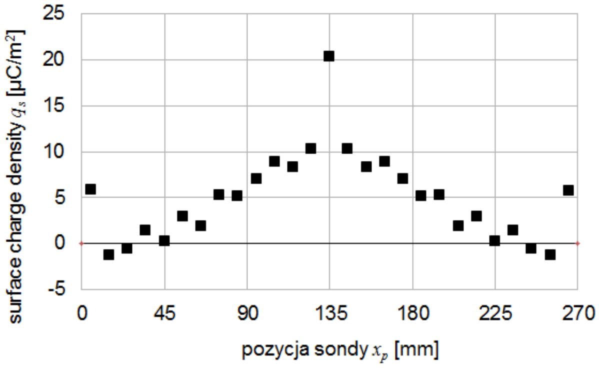

Fig. 2. Exemplary surface charge density distribution along insulator generatrix

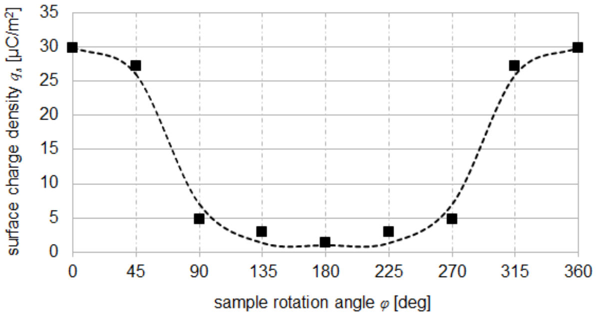

Fig. 3. Exemplary surface charge density distribution along insulator perimeter

Total charge deposited on insulator surface was on the level of Q_t ≈ 60 nC. Measurements of total charge Q_t were made using the Faraday cage

Experiment and results

Insulating surface of each model was de-electrified before each test. Depolarization was carried out by cleaning whole insulating surface by an earthed, ethanol soaked cotton tampon. The potential on depolarized model do not exceed ±50 V and have often negative polarity.

Then, optionally, the insulator was electrified by corona discharge. Electrification voltage was 40 kV and the electrification time was 10 s. Next insulator was removed from the area of electrification with the voltage on the corona-electrode still present (in order to eliminate back discharge).

Next insulator was mounted in system for testing DC flashover voltage. DC voltage was applied with average slope of 2.75 kV/s voltage to the point of the flashover.

One measurement series contains flashover measurements for samples de-electrified and charged with hetero- or homo-charge (Q_t ≈ ±60 nC). 35 measurement series were made, including:

- 23 series in „up” position;
- 12 series in „down” position.

Measured flashover voltage for de-electrified samples was shown in table 3.

Table 3.Average values of measured flashover values U_f for de-electrified samples

Polarity\Position	Up	Down
Positive	174 kV	153 kV
Negative	162 kV	193 kV

Empirical data match the calculation. It should be noted that changing the position of the insulator changes the voltage flashover at the level of 16% average.

In order to determine the charge influence on flashover voltage U_f introduced three factors defined as follows:

$$k_{hetero/0} == \left(\frac{U_{f(hetero)}}{U_{f(0)}}-1\right)\cdot 100\% \qquad (2)$$

$$k_{homo/0} = \left(\frac{U_{f(homo)}}{U_{f(0)}}-1\right)\cdot 100\% \qquad (3)$$

$$k_{homo/hetero} = \left(\frac{U_{f(homo)}}{U_{f(hetero)}}-1\right)\cdot 100\% \qquad (4)$$

where: $U_{f(0)}$ – average flashover voltage on insulator without charge, $U_{f(homo)}$ – average flashover voltage on insulator with a homo-charge, $U_{f(hetero)}$ – average flashover voltage on insulator with a hetero-charge.

It was assumed (based on measurement uncertainty) that if k-factor value is less than ±2%, the charge does not affect the flashover voltage U_f.

One measurement series with addition measurements for Q_t = ±40nC is shown in Fig. 4.

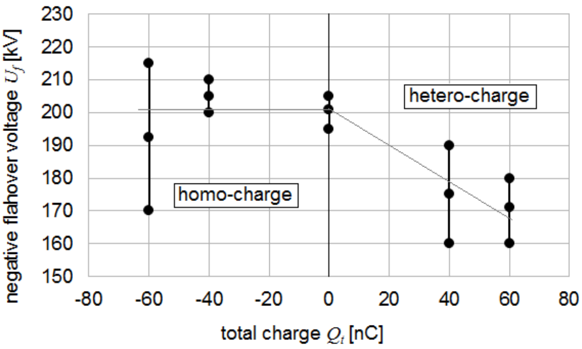

Fig. 4. Flashover voltage values dependence on the total charge. The charge was in the middle, and the insulator was in the "down" position, negative voltage polarity was applied

For presented series $k_{hetero/0}$ is equal to -15% (for Q_t = 60 nC) or -13% (for Q_t = 40 nC), and $k_{homo/0}$ is equal to to -4% (for Q_t = 60 nC) or +2% (for Q_t = 40 nC). For Q_t = 60 nC the value of $k_{homo/hetero}$ is 12% (for Q_t = 60 nC). It can be see that hetero–charge clearly decreases, but homo-charge does not change flashover voltage.

Frequency of occurrence histograms of k-factors are presented in Fig. 5-7.

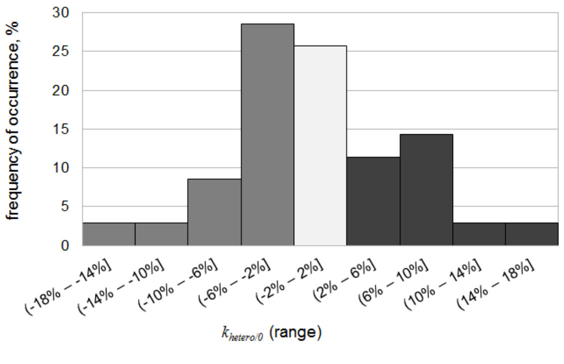

Fig. 5. Frequency of occurrence values of $k_{hetero/0}$ (ranges) for 35 measurement series

The spread of the values of $k_{hetero/0}$ is in the range from -15% to +15%. In 26% of measurements series – $U_{f(hetero)} \approx U_{f(0)}$, in 43% – $U_{f(hetero)} < U_{f(0)}$ (average $k_{hetero/0}$ value in this case was -5,7%), in 31% – $U_{f(hetero)} > U_{f(0)}$ (average $k_{hetero/0}$ value in this case was +7,1%). Tendency towards $U_{f(hetero)} \leq U_{f(0)}$ is visible.

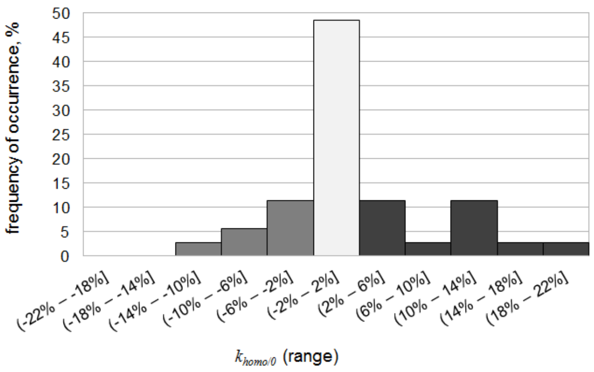

Fig. 6. Frequency of occurrence values of $k_{homo/0}$ (ranges) for 35 measurement series

The spread of the values of $k_{homo/0}$ is in the range from -11% to +18%. In 49% of measurements series – $U_{f(homo)} \approx U_{f(0)}$, in 20% - $U_{f(homo)} < U_{f(0)}$ (average $k_{homo/0}$ value in this case was -5,7%), in 32% – $U_{f(homo)} > U_{f(0)}$ (average $k_{homo/0}$ value in this case was +9%). Tendency towards $U_{f(homo)} \approx U_{f(0)}$ or $U_{f(homo)} \geq U_{f(0)}$ is visible.

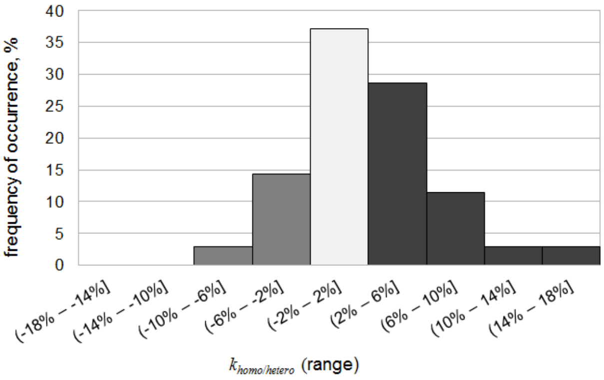

Fig. 7. Frequency of occurrence values of $k_{homo/hetero}$ (ranges) for 35 measurement series

The spread of the values of $k_{homo/hetero}$ is in the range from -6% to +18%. In 37% of measurements series – $U_{f(homo)} \approx U_{f(hetero)}$, in 17% – $U_{f(homo)} < U_{f(hetero)}$ (average $k_{homo/hetero}$ value in this case was -4,3%), in 46% – $U_{f(homo)} > U_{f(0)}$ (average $k_{homo/hetero}$ value in this case was +5,6%). Tendency towards $U_{f(homo)} \geq U_{f(hetero)}$ is visible.

It is visible asymmetry of results in this sense that hetero-charge decreases and homo-charge not affect the value of flashover voltage (same as in Fig. 4). This phenomenon can be explained by asymmetric charge distribution around the perimeter of the insulator – as seen in Fig. 8.

According to the simulation data (given in Fig. 8), if a charge has the same sign as the polarity of voltage on the HV-fitting, then on side of charge deposition occur a significant reduction of the E_{max} field strength. On the opposite side of insulator reduction of the field strength is minimal (Fig. 8 a). Higher field strength value occurs on the side opposite to the place of charge deposition and it does not differ significantly from the values of the maximum field E_{max} strength for uncharged insulator. Therefore there is no reason for flashover voltage on charged insulator (with homo-charge) - $U_{f(homo)}$, to be significantly different from the flashover voltage for uncharged insulator - $U_{f(0)}$.

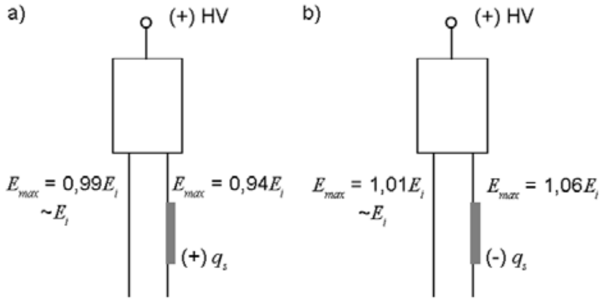

Fig. 8. The influence of asymmetric charge distribution around perimeter on the value of the maximum electric field. a) homo-charge, b) hetero-charge. E_{max} – the maximum value of the field, E_i – the maximum value of the field strength of the insulator without charge

If the charge has a sign opposite to the polarity of the voltage on the HV-fitting (Fig. 7.b), then on side of charge deposition an increase of the E_{max} field strength occurs. On the opposite side increase in the intensity of the field is minimal. The higher value of the field strength occurs on the side where charge was deposited, and is significantly higher than E_{max} for uncharged insulator. It follows that the presence of hetero-charge will reduce flashover voltage, thus $U_{f(hetero)} < U_{f(0)}$.

This analysis allows us to formulate 3 conclusions in the form of flashover voltage relations:

- $U_{f(hetero)} < U_{f(0)}$;
- $U_{f(homo)} \approx U_{f(0)}$;
- $U_{f(homo)} > U_{f(hetero)}$.

These relations are consistent with the results obtained.

Values of k-factors for position “up” and “down” are presented in table 4.

Table 4. Average values of k-factor for tested positions

Position\Factor	$k_{hetero/0}$	$k_{homo/0}$	$k_{homo/hetero}$
Up	0,54%	1,76%	1,19%
Down	-1,78%	1,44%	3,60%

For position “down” hetero-charge influence on U_f is slightly larger. Influence of homo-charge is lower, hoverer this is closer to expected result ($U_{f(homo)} \approx U_{f(0)}$).

Conclusion

Deposited charge ($Q_t \approx$ 60 nC) affects the field around the tested models insulators and thus the value of the flashover voltage. Charge influence on flashover voltage at the level of 0 - 18% was observed. In significant number of cases (25 - 50%) the charge influence was in the range of 0 - ±2% (in range of measurement uncertainty).

Hetero-charge decreases flashover voltage value U_f while the homo-charge does not affect it.

The simulations and empirical results indicate that the shape of the fittings (micro-blades) and the insulator surrounding (space charge, insulator position in relation to grounded object) can affect the value of the flashover voltage on similar level to charge deposited on insulator. The influence of the charge on the flashover voltage significantly depends on factors mentioned previously, it is therefore difficult to predict and should each time be empirically verified, under conditions similar to operating conditions.

Because of the ambiguity of the results and the potential impact of a number of factors further studies of described phenomenon are necessary.

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